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Development of Bushing Compounds for Tracked Vehicles

Prepared by
Paul E. Gatza
and
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Report Date
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United States Army
Belvoir Research, Development and Engineering Center
Fort Belvoir, Virginia 22060-5606

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PREFACE

This report details compounding studies, tests conducted, and results obtained in efforts to develop elastomeric components having improved performance characteristics and greater service life in bushing assemblies of tracked vehicles. A database, generated from the evaluation of vendor's typical off-the-shelf materials, was used to establish requirements criteria. Prototype bushings were fabricated from selected optimum candidate compounds, and simulated endurance performance evaluation was conducted by Michigan Technological University, Houghton, MI.

Tables referred to in this report are found in the Appendix.

SECTION I — BACKGROUND

Total superior performance of the Army's family of tracked vehicles, such as the M1, M60, and Bradley Fighting Vehicle, is obviously contingent upon the reliability and life of the track itself. Unfortunately, this essential component has gained the same reputation as an unwanted stepchild — part of the family (system), but devoid of needed attention. Lacking the aura enjoyed by sophisticated electronic control equipment or weaponry, track system quality and reliability has not kept pace with progress and improvements attained elsewhere relative to vehicle performance optimization. Only recently has there been any effort by the cognizant Tank Automotive Command (TACOM) to design track systems and components thereof, capable of withstanding increased vehicle weight, ground pressures, and other demands imposed by technological changes.

As an initial step in that effort, TACOM provided funding to the Belvoir Research, Development and Engineering Center's Rubber and Coated Fabrics Research Group for the development of track pads having a longer service life, thereby reducing down time and replacement costs. The physical and mechanical characteristics of pad vendor's elastomer compounds were determined to assemble a database and draft target performance requirements. Numerous compound formulation, mixing, vulcanization, and testing iterations were then performed, including some employing previously untried base polymers, fillers, and vulcanization systems. A compound, based on the relatively new hydrogenated nitrile polymer, was found to offer unique properties

deemed advantageous for performance optimization. While ability to withstand heat build-up (blowout resistance) appeared questionable, resistance to abrasion, cutting, chipping, and flexing was excellent. On-vehicle testing of pads fabricated from this so-called and patented NBR-12 formulation indicated that service life could be doubled or even tripled up to between 2,000 and 3,000 miles.

When considering the logistics of vehicle track, it is apparent that extension of pad service life is meaningless if other components, such as the pins or bushings, fail earlier. Ideally, equivalent life expectancy for all components must be realized to achieve total system optimization. This was vividly demonstrated when TACOM evaluated the German Diehl track, used on their Leopard family of tanks. While the track hardware remained serviceable after over 2,000 miles of on-course testing at the Yuma Proving Grounds, AZ, the pads lasted less than half as long. Bushings currently used in the M1 track assembly typically fail after 1,500 to 1,700 miles of use. Thus, longer service life achieved through conversion to hydrogenated nitrile pads would be negated by the continuing need for bushing replacement.

A need to upgrade bushing performance and service life became self-evident. By utilizing an approach similar to that described for the pad development program, perhaps bushing longevity could also be increased. If not immediately successful, at least such an effort would result in establishment of a database for proper direction of continuing or future effort.

SECTION II — INVESTIGATION

VENDORS' COMPOUNDS

In their unvulcanized state, approximately 5 to 7 pounds of four compounds presently used to fabricate track bushings were obtained from known industry suppliers. Using conventional rheometric procedures, the optimum time/temperature cure parameters were determined for each material. A test

matrix was established by drawing upon experience in the pad compound development work, and assessing properties judged critical to optimum bushing performance. ASTM test sheets, 6 x 6 x .080 inch, and specimens unique to conducting specific physical and dynamic tests were prepared. The following tests were conducted and applicable ASTM methods used:

| | |
|--|----------------------|
| Tensile Strength, Elongation, 200% Modulus | |
| Unaged | ASTM D-412 |
| 46 Hours at 250°F | ASTM D-573, D-412 |
| 46 Hours at 300°F | ASTM D-573, D-412 |
| Hardness, Shore A | ASTM D-2240 |
| Specific Gravity | ASTM D-792 |
| Bashore Resilience | ASTM D-2632 |
| Tear Strength | |
| Unaged | ASTM D-624, Die C |
| 4 Hours at 250°F | ASTM D-624, Die C |
| 4 Hours at 300°F | ASTM D-624, Die C |
| Compression (Load) Deflection | ASTM D-575, Method B |
| Compression Set | |
| 22 Hours at 160°F | ASTM D-395 |
| 46 Hours at 212°F | ASTM D-395 |
| 22 Hours at 250°F | ASTM D-395 |
| 22 Hours at 300°F | ASTM D-395 |
| DeMattia Crack Growth | |
| Unaged | ASTM D-813 |
| 20 Hours at 250°F | ASTM D-813 |
| Ross Flex, 250,000 Cycles | |
| Unaged | ASTM D-1052 |
| 20 Hours at 250°F | ASTM D-1052 |
| Goodrich Flex at 122°F | ASTM D-623 |
| Brittleness at -40°F, 7 Days | ASTM D-2137 |

Heat-aged dumbbells and compression set specimens were subsequently tested at room temperature. All other specimens were tested at the indicated aging temperature.

COMPOUNDING STUDIES

Upon completion of all testing, the data generated were analyzed to determine performance patterns, similarities and differences, and any apparent signals indicating where desired properties could or should be improved. Numerous formulations—based on natural rubber, propylene oxide, and silicone—were mixed, vulcanized, and subjected to the same test program used to characterize the vendor's bushing compounds. If it was apparent from examination of the initial data that a compound was grossly deficient in a key performance factor, further testing was discontinued. Eventually, 13 compounds—6 based on natural rubber, 3 based on

propylene oxide, and 4 based on silicone—displayed sufficient promise to have been subjected to all tests listed in the matrix.

RESULTS

Tables 1 and 2 (see Appendix for all tables referenced herein) summarize all test data generated for the vendors' bushing compounds. (Formulations of vendor's compounds are considered proprietary.) Tables 3 and 4 contain the formulations of selected candidate natural rubber, propylene oxide, and silicone rubber compounds. Corresponding data for each of the three base polymer groupings are summarized in Tables 5 through 10. Tables 2, 6, 8, and 10 contain no data, merely plus and minus signs denoting whether a compound passed or failed a particular test. This approach has been found to be helpful when analyzing for performance patterns or trends, or when a quick means of assessment is desired.

SECTION III — DISCUSSION

BUSHING REQUIREMENTS

At the time of preparation of this report, MIL-T-11891, the specification referencing requirements for track assembly bushings (and pads) is under revision. A PD, or purchase description, is the temporary governing document as maintained by TACOM. The PD incorporates Statistical Process Control (SPC) techniques for control of item quality. Citing of requirements per se, such as actual values for tensile strength, elongation, etc., has essentially been eliminated. In the case of requirements for the bushings, only a load deflection range

requirement of 33 to 41%, and heat aging temperatures of 212°F and 250°F, as well as some definite aging periods, are explicitly specified. Thus, when attempting to assemble a definitive set of target performance requirements, one must either extract information from older versions of MIL-T-11891, have access to some relevant data base, or rely upon knowledge, experience, and intuition. The target or desired properties listed in the data tables are therefore a compendium of all of the above, and not meant to be interpreted as a hard and fast set of unbreakable rules. The game of rubber compound optimization often involves compromise if success is to be achieved.

TEST RESULTS

Vendors' Compounds

It is evident from a cursory review of the selected target performance properties that considerable emphasis was placed upon factors such as ability to withstand heat buildup, flexing, and compressive forces. Attributes such as resistance to cutting, chipping, and abrasion, deemed essential in pads, are not requisite for bushings. MIL-T-11891 cites bushing fill, adhesion, and torque criteria; however, lack of proper molding and testing equipment precluded consideration of these performance characteristics.

Examination of the physical data of Table 1 and the conformance (pass/fail) summarization of Table 2 indicates that Bush-5 would be the preferred compound. While it displayed excessive external temperature rise in the Goodrich flex test and poorest tear strength at 250°F, rebound and DeMattia flex resistance were superior. Additionally, Bush-5 was the only compound evidencing conforming compression set resistance at the lowest test temperature of 160°F, and subsequently at 212°F and 250°F. None of the compounds fared well relative to aged tensile properties, but Bush-5 did manage to retain approximately 50% of both tensile and elongation after exposure at 250°F. Anomalies noted in the tear test data at elevated temperatures, and other observed trends in heat-influenced properties, led to the conclusion that good heat resistance is sacrificed for the sake of achieving adequate initial tear strength. Results of end item evaluations of these materials conducted at Michigan Technological University support preference for compound Bush-5.

Natural Rubber Compounds

Innovative compounding approaches employed in the pad development program provided a base for selection of natural rubber formulations considered having potential for bushings. By discounting abrasion and related pad wear factors, modifications to filler and curing systems could be made to hopefully enhance other properties. As shown in Table 3, four of the six formulations contain a zinc methacrylate-based filler system, four employ a peroxide curing system, and all contain processing aids which are purported to also augment relevant performance characteristics.

Certain isolated instances of distinct property enhancement, such as the two cases of Bashore rebound exceeding 60 (NAT-148A and NAT-158), the high unaged tear strength of NAT-127A, and more consistently better performance in the unaged and aged DeMattia and Ross flex tests, are readily discernable from Tables 5 and 6. Most significant perhaps is the marked improvement in tensile and elongation retention after aging at 250°F. All compounds retained between 54% and 90% of their original tensile strength and elongation, and three (NAT-127A, NAT-157, and NAT-158) had acceptable compression set. All of the vendor's compounds satisfied the requirement for maximum internal temperature rise in the Goodrich flex test, while only three natural rubber compounds did. The failures (NAT-155A, NAT-127A, and NAT-157) could possibly be attributed to inability to compromise high tear strength and good flex resistance while in the compressive mode of the Goodrich test. NAT-158 was clearly the best performing candidate. NAT-155A, which demonstrated a good balance of properties and highest aged tear values, would be the preferred second choice.

Propylene Oxide Compounds

Formulations based upon the relatively unknown and little-used propylene oxide elastomer (Table 4), are not noted for processing ease or development of high tensile strength. Nevertheless, they have sufficient redeeming qualities, such as heat resistance, high resilience, and low temperature serviceability, making them worthy of consideration in this study. The three compounds shown in Table 4 exemplify a relatively basic formulation (PO-19 and PO-19A, the latter only differing in that it was post-cured), and an attempt to ascertain whether a zinc methacrylate-base 1 filler system could augment performance (PO-22). Data for these compounds and a pass-fail summarization are found in Tables 7 and 8, respectively.

As expected, all three compounds displayed low tensile strength values—1,000 psi below the desired. PO-22 also displayed low elongation and high Shore A hardness, thus precluding any further serious consideration as a candidate for end item fabrication. Resistance to tear and performance in the DeMattia and Ross flex tests were poor in all cases, but Goodrich flex results for PO-19 and PO-19A were acceptable. Superiority to natural rubber, relative to heat resistance, is clearly evident. Only PO-19A satisfied all compression set limits, but all evidenced good retention of tensile strength and elongation at 300°F. As noted at the bottom of Tables 1 and 5, both the vendors' and the natural rubber compounds could not be tested after aging at that temperature. Post-curing, commonly used and sometimes necessary for fluorocarbon, silicone, and other elastomers, did appear to enhance certain properties of the

PO-19A variant. From a practical standpoint, however, some doubt existed as to whether the complex bushing configuration would respond properly to post-curing. PO-19 was thus selected for subsequent end item fabrication.

Silicone Compounds

A rubber compounder has little latitude when dealing with silicones. Other than varying the type or amount of curative or adding a coloring agent, the compounder must work with the material as provided by the supplier. A further disadvantage—price—dictates limitations on cost-effective usage. Known poor tensile and tear strengths are offset by excellent heat resistance and dynamic properties.

Inclusion here was based on awareness and importance of the latter positive factors. The four compounds listed in Table 4 were chosen after a review of recommendations provided by industry suppliers. Blending of two or more polymers tends to result in a product combining the worst features of each. Here, as in compound SI-8, an equitable compromise was the intent.

Knowing that these compounds would meet target compression set, and heat-aged tensile and elongation requirements, certain tests were not performed to conserve time and material costs. As indicated in Tables 9 and 10, all silicone candidates did indeed display low initial tensile strength and 200% moduli. Initial tear resistance was also poor, but proportionately better than that of the natural rubber and propylene oxide compounds at 250°F and 300°F. Resilience and compression deflection were marginal while

flexural properties were mixed. Excellent across-the-board results in the DeMattia testing were contrasted by isolated instances of acceptability under the Ross and Goodrich criteria. Performance of SI-6 and SI-7 was

noticeably poorer than that of SI-5 and SI-8. The distinctly better tear strength and near conformance in the Goodrich test of SI-8 led to its ultimate selection for further evaluation.

SECTION IV — BUSHING FABRICATION AND TESTING

COMPOUND SELECTION AND MOLD FABRICATION

None of the thirteen compounds evaluated satisfied all of the target criteria deemed essential to optimization of bushing performance. Four candidates—NAT-158, NAT-155A, PO-19, and SI-8—were judged worthy of further study; namely, fabrication into end items and simulated in-service testing. Arrangements were made with the Michigan Technological University (MTU), which has appropriate test capabilities to conduct the bushing endurance test specified in the purchase description being used in lieu of MIL-T-11891. Thus, a mold configured to the dimensional requirements for T130 bushings—those used on M113 vehicles and for MTU testing—was requested and fabricated by the in-house machine shop.

ADHESION STUDIES

Upon delivery of the mold, studies were conducted to determine the best commercially available adhesive or primer/ adhesive system for bonding the bushing rubber to accompanying axial metal rods which complement a complete track assembly. An existing fixture which can be bolted to the table of an Instron Universal Testing Machine was modified to accommodate the finished items. Separation of the rubber from the metal was initiated at one end of each test specimen to provide material for gripping by the moveable upper clamp. During subsequent raising of the crosshead and recording of adhesion values, compensating movement of the test fixture allowed the plane of separation to remain perpendicular at all times. Several adhesive systems, as recommended by commercial suppliers, were evaluated. Results obtained are tabulated on page 7.

| Compound | Adhesive | Test Results (pounds) |
|---------------------|--------------------|-----------------------|
| PO-19 | Chemlock 205 + 246 | 24* |
| SI-8 | Chemlock 607 | 28* |
| SI-8 | Thixon 305 | 18 |
| NAT-155A | Chemlock 205 + 252 | 24* |
| NAT-155A | Thixon P-6-1 + 508 | 19 |
| NAT-155A | Thixon P-14 + 508 | 21 |
| NAT-158 | Chemlock 205 + 252 | 24* |
| NAT-158 | Thixon P-6-1 + 508 | 24 |
| Commercial Compound | — | 33 |

**Compound/adhesive systems were ultimately selected for use in final molding of bushings sent to MTU for endurance testing.*

BUSHING PERFORMANCE EVALUATION

Two prototype bushings were fabricated from compound SI-8, and four each from compounds NAT-158, NAT-155A, and PO-19. The endurance test apparatus at Keweenaw Research Center, MTU, is configured to conform to requirements originally contained in MIL-T-11891D, and considered valid as stated in the presently used purchase description. Test constraints are 5,200 pounds radial force at 64 cycles per minute (CPM) and $\pm 15^\circ$ at 256 CPM. When a deflection of .145 inches is reached, the test is terminated. Bushing temperature, number of cycles, and deflection attained are continuously recorded for translation to a graphical record. For comparison purposes, bushings fabricated from the four vendors' compounds were also tested. Bushing endurance performance data provided by MTU was disappointing. All of the chosen laboratory compounds reached the maximum allowable deflection after completing a relatively low number of cycles,

attributable to loss of adhesion at the rubber/metal interface. Three of the four vendors' compounds attained over 100,000 cycles, while the best in-house candidate (NAT-158) averaged 22,500 cycles. Compounds SI-8 and PO-19 failed after completing less than 200 cycles and NAT-155A averaged slightly better than 14,000 cycles. Visual examination of the bushings after test termination verified the adhesion failures. Heat buildup within vendors' compounds and the two natural rubber candidates was comparable in the 115°F to 140°F range. This would tend to negate any supposition that adhesion failures were entirely due to thermal deterioration of bonded surfaces. True, the magnitude of the bond strength noted for the vendors' compounds tested was higher, but exact cause/effect relationships are indiscernable. It is apparent however, that further effort in bushing performance improvement should be directed toward addressing the adhesion problem.

SECTION V — CONCLUSIONS

- Optimization of all physical and dynamic properties deemed requisite for extended-life bushing performance is extremely difficult.
- Elastomeric bushing compounds currently supplied by vendors display only moderate resistance to flexing and tear, and poor retention of initial tensile strength and elongation at temperatures of 250°F and above.
- Significant improvement in specific performance requirements is attainable through proper choice of base polymers and compounding ingredients.
- Further effort is necessary to ascertain the extent to which physical and dynamic properties can be compromised in the interest of extending bushing service life.
- Final judgment of the performance potential of candidate bushing compounds evaluated in this program is contingent upon resolution of rubber/metal adhesion problems and results of additional endurance testing.

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Table 1. Physical Properties—Vendors' Bushing Compounds

| MATERIAL ID | | BUSH-1 | BUSH-3 | BUSH-4 | BUSH-5 |
|----------------------------------|----------------|---------------|---------------|---------------|---------------|
| Original Properties | Desired | | | | |
| Tensile Strength, psi | >2700 | 4000 | 3860 | 3910 | 3790 |
| 200% Modulus, psi | >700 | 870 | 1085 | 1340 | 820 |
| Elongation, % | >350 | 575 | 500 | 430 | 530 |
| Hardness, Shore A Points | 65 - 75 | 68 | 70 | 72 | 68 |
| Bashore Rebound, % | >50 | 43 | 45 | 47 | 51 |
| Compression Deflection, % | 33 - 41 | 36 | 34 | 33 | 39 |
| Specific Gravity | — | 1.139 | 1.1374 | 1.1144 | 1.127 |
| Press Cure, min/°F | — | 50/300 | 35/300 | 30/290 | 10/310 |
| Oven Post Cure, hrs/°F | — | — | — | — | — |
| Tear Strength; ASTM Die C, lb/in | | | | | |
| Unaged | >300 | 318 | 362 | 486 | 315 |
| 4 hours @ 250°F | >175 | 180 | 138 | 132 | 179 |
| 4 hours @ 300°F | >150 | 171 | 172 | 190 | 62 |
| Brittleness, 7 days @ -40°F | Pass | Pass | Pass | Pass | Pass |
| Fatigue Properties | | | | | |
| Ross Flex, 250,000 Cycles | | | | | |
| Unaged Crack Growth, % | <100 | 111 | 33 | 64 | 67 |
| Aged 20 hours @ 250°F | | | | | |
| Crack Growth, % | <300 | 428 | 700 | Fail | Fail |
| DeMattia Flex | | | | | |
| Unaged Growth Rate, mils/min | <25 | 18 | 18 | 20 | 13.5 |
| Aged 20 hours @ 250°F | | | | | |
| Growth Rate, mils/min | <200 | 575 | 575 | 593 | 65.3 |
| Goodrich Flex @ 50°C | | | | | |
| Temperature Rise | | | | | |
| External, °C | <25 | 20 | 22 | 20 | 29 |
| Internal, °C | <50 | 46 | 48 | 46 | 45 |
| Heat Resistance | | | | | |
| at 160°F | | | | | |
| Compression Set, % (22 hrs) | <25 | 37 | 40 | 39 | 19 |
| at 212°F | | | | | |
| Compression Set, % (46 hrs) | <40 | 60 | 56 | 53 | 38 |
| at 250°F | | | | | |
| Elongation Retention, % | >70 | 6 | 11 | 12 | 45 |
| Tensile Retention, % | >70 | 15 | 62 | 17 | 55 |
| Compression Set, % (22 hrs) | <50 | 64.5 | 64.1 | 60 | 47 |
| at 300°F | | | | | |
| Elongation Retention, % | >60 | A | A | A | A |
| Tensile Retention, % | >60 | A | A | A | A |
| Compression Set, % (22 hrs) | <60 | 94.6 | 92.8 | 89.2 | 65 |

Note: (A) Material lost too much integrity to test.

Table 2. Conformance (Pass/Fail)—Vendors' Bushing Compounds

| MATERIAL ID | | BUSH-1 | BUSH-3 | BUSH-4 | BUSH-5 |
|----------------------------------|----------------|---------------|---------------|---------------|---------------|
| Original Properties | Desired | | | | |
| Tensile Strength, psi | >2700 | + | + | + | + |
| 200% Modulus, psi | >700 | + | + | + | + |
| Elongation, % | >350 | + | + | + | + |
| Hardness, Shore A Points | 65 – 75 | + | + | + | + |
| Bashore Rebound, % | >50 | – | – | – | + |
| Compression Deflection, % | 33 – 41 | + | + | + | + |
| Tear Strength; ASTM Die C, lb/in | | | | | |
| Unaged | >300 | + | + | + | + |
| 4 hours @ 250°F | >175 | + | – | – | + |
| 4 hours @ 300°F | >150 | + | + | + | – |
| Brittleness, 7 days @ –40°F | Pass | + | + | + | + |
| Fatigue Properties | | | | | |
| Ross Flex, 250,000 Cycles | | | | | |
| Unaged Crack Growth, % | <100 | – | + | + | + |
| Aged 20 hours @ 250°F | | | | | |
| Crack Growth, % | <300 | – | – | – | – |
| DeMattia Flex | | | | | |
| Unaged Growth Rate, mils/min | <25 | + | + | + | + |
| Aged 20 hours @ 250°F | | | | | |
| Growth Rate, mils/min | <200 | – | – | – | + |
| Goodrich Flex @ 50°C | | | | | |
| Temperature Rise | | | | | |
| External, °C | <25 | + | + | + | – |
| Internal, °C | <50 | + | + | + | + |
| Heat Resistance | | | | | |
| at 160°F | | | | | |
| Compression Set, % (22 hrs) | <25 | – | – | – | + |
| at 212°F | | | | | |
| Compression Set, % (46 hrs) | <40 | – | – | – | + |
| at 250°F | | | | | |
| Elongation Retention, % | >70 | – | – | – | – |
| Tensile Retention, % | >70 | – | – | – | – |
| Compression Set, % (22 hrs) | <50 | – | – | – | + |
| at 300°F | | | | | |
| Elongation Retention, % | >60 | – | – | – | – |
| Tensile Retention, % | >60 | – | – | – | – |
| Compression Set, % (22 hrs) | <60 | – | – | – | – |

Table 3. Experimental Compounds—Natural Rubber

| INGREDIENTS | NAT-148A | NAT-155A | NAT-127A | NAT-95A | NAT-157 | NAT-158 |
|---------------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|
| Natural Rubber | 100.0 | 100.0 | 100.0 | 100.0 | 80.0 | 100.0 |
| Vestenamer 8012 | — | — | — | — | 20.0 | — |
| Zinc Oxide | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 2.00 |
| Stearic Acid | — | — | 1.00 | 1.50 | — | — |
| Struktol A60 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | — |
| NBC | — | — | — | — | — | — |
| Agerite Resin D | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| Vanox MTI | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Santoflex 13 | 1.50 | 1.50 | 2.50 | 2.50 | 1.50 | — |
| N-330, HAF Black | 25.00 | 25.00 | 45.00 | — | 25.00 | 25.00 |
| CAB-O-SIL, MS-7SD | — | — | — | 40.00 | — | — |
| Z MAX MA | 20.00 | 35.00 | — | — | 35.00 | 20.00 |
| Akrochem P-87 Resin | — | — | — | — | — | 10.00 |
| Sulfur | — | — | 0.40 | — | — | — |
| Vulcanox ZMB2 | — | — | 2.00 | — | — | — |
| Novor 924 | — | — | 4.20 | — | — | — |
| Santocure NS | — | — | 0.10 | — | — | — |
| TMTM, Monex | — | — | 1.80 | — | — | — |
| Santocure MOR | — | — | — | 4.00 | — | — |
| Methyl Ethyl Tuads | — | — | — | 3.00 | — | — |
| DICUP R | 2.50 | 1.20 | — | — | 1.20 | 1.30 |

Table 4. Experimental Compounds—Propylene Oxide and Silicone**PROPYLENE OXIDE COMPOUNDS**

| INGREDIENTS | PO-19 | PO-19A | PO-22 |
|--------------------|--------------|---------------|--------------|
| Parel 58 | 100.00 | 100.00 | 100.00 |
| Zinc Oxide | 5.00 | 5.00 | — |
| Stearic Acid | 1.00 | 1.00 | — |
| NBC | 1.00 | 1.00 | — |
| Agerite Resin D | — | — | 1.50 |
| Vanox MTI | — | — | 0.50 |
| N-550 FEF Black | 50.00 | 50.00 | — |
| N-990, Thermax, MT | — | — | 5.00 |
| CAB-O-SIL, MS-7SD | — | — | 25.00 |
| Z MAX MA | — | — | 25.00 |
| Sulfur | 0.70 | 0.70 | — |
| Methyl Tuads | 1.10 | 1.10 | — |
| Dicup R | — | — | 1.50 |

SILICONE COMPOUNDS

| INGREDIENTS | SI-5 | SI-6 | SI-7 | SI-8 |
|------------------------|-------------|-------------|-------------|-------------|
| SWS-C986 | 100.00 | — | — | — |
| SWS-7675U | — | 100.00 | — | — |
| SIL-HS975 | — | — | 100.00 | 50.00 |
| SIL-HS950 | — | — | — | 50.00 |
| Silastic HT-1 Modifier | — | — | 0.70 | 0.70 |
| Lupercu 101XL | 1.00 | 0.80 | 1.00 | 1.00 |

Table 5. Physical Properties—Natural Rubber Compounds

| MATERIAL ID | | NAT-148A | NAT-155A | NAT-127A | NAT-95A | NAT-157 | NAT-158 |
|----------------------------------|----------------|----------|----------|----------|---------|---------|---------|
| Original Properties | Desired | | | | | | |
| Tensile Strength, psi | >2700 | 4453 | 3850 | 3710 | 4683 | 3020 | 3240 |
| 200% Modulus, psi | >700 | 1323 | 1067 | 723 | 290 | 1123 | 1400 |
| Elongation, % | >350 | 450 | 460 | 590 | 710 | 420 | 380 |
| Hardness, Shore A Points | 65 - 75 | 70 | 72 | 74 | 67 | 76 | 66 |
| Bashore Rebound, % | >50 | 61 | 54 | 46 | 45 | 51 | 66 |
| Compression Deflection, % | 33 - 41 | 37 | 35 | 38 | 44 | 32 | 38 |
| Specific Gravity | — | 1.113 | 1.135 | 1.1211 | 1.1294 | 1.1556 | 1.0904 |
| Press Cure, min/°F | — | 50/320 | 55/320 | 20/330 | 50/300 | 40/330 | 40/330 |
| Oven Post Cure, hrs/°F | — | — | — | — | — | — | — |
| Tear Strength; ASTM Die C, lb/in | | | | | | | |
| Unaged | >300 | 310 | 415 | 510 | 342 | 269 | 302 |
| 4 hours @ 250°F | >175 | 208 | 355 | 203 | 184 | 97 | 165 |
| 4 hours @ 300°F | >150 | 178 | 203 | 180 | 132 | 117 | 124 |
| Brittleness, 7 days @ -40°F | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| Fatigue Properties | | | | | | | |
| Ross Flex, 250,000 Cycles | | | | | | | |
| Unaged Crack Growth, % | <100 | 42 | 33 | 133 | 150 | 33 | 67 |
| Aged 20 hours @ 250°F | | | | | | | |
| Crack Growth, % | <300 | 33 | 33 | 75 | Fail | 58 | 217 |
| DeMattia Flex | | | | | | | |
| Unaged Growth Rate, mils/min | <25 | 12 | 11 | 10 | 14 | 11 | 20 |
| Aged 20 hours @ 250°F | | | | | | | |
| Growth Rate, mils/min | <200 | 20 | 10 | 18 | 29 | 11 | 54 |
| Goodrich Flex @ 50°C | | | | | | | |
| Temperature Rise | | | | | | | |
| External, °C | <25 | 17 | 25 | 27 | 19 | 38 | 16 |
| Internal, °C | <50 | 48 | 72 | 64 | 46 | 85 | 38 |
| Heat Resistance | | | | | | | |
| at 160°F | | | | | | | |
| Compression Set, % (22 hrs) | <25 | 26 | 29 | 29 | 38 | 29 | 23 |
| at 212°F | | | | | | | |
| Compression Set, % (46 hrs) | <40 | 38 | 47 | 44 | 64 | 42 | 35 |
| at 250°F | | | | | | | |
| Elongation Retention, % | >70 | 83 | 85 | 73 | 90 | 78 | 83 |
| Tensile Retention, % | >70 | 60 | 54 | 67 | 69 | 55 | 57 |
| Compression Set, % (22 hrs) | <50 | 51 | 55 | 49 | 69 | 45 | 34 |
| at 300°F | | | | | | | |
| Elongation Retention, % | >60 | A | A | A | A | A | A |
| Tensile Retention, % | >60 | A | A | A | A | A | A |
| Compression Set, % (22 hrs) | <60 | 65 | 78 | 69 | 91 | 65 | 42 |

Note: (A) Material lost too much integrity to test.

Table 6. Conformance (Pass/Fail)—Natural Rubber Compounds

| MATERIAL ID | | NAT-148A | NAT-155A | NAT-127A | NAT-95A | NAT-157 | NAT-158 |
|----------------------------------|---------|----------|----------|----------|---------|---------|---------|
| Original Properties | Desired | | | | | | |
| Tensile Strength, psi | >2700 | + | + | + | + | + | + |
| 200% Modulus, psi | >700 | + | + | + | - | + | + |
| Elongation, % | >350 | + | + | + | + | + | + |
| Hardness, Shore A Points | 65 - 75 | + | + | + | + | + | + |
| Bashore Rebound, % | >50 | + | + | - | - | + | + |
| Compression Deflection, % | 33 - 41 | + | + | + | - | + | + |
| Tear Strength; ASTM Die C, lb/in | | | | | | | |
| Unaged | >300 | + | + | + | + | - | + |
| 4 hours @ 250°F | >175 | + | + | + | + | - | - |
| 4 hours @ 300°F | >150 | + | + | + | - | - | - |
| Brittleness, 7 days @ -40°F | Pass | + | + | + | + | + | + |
| Fatigue Properties | | | | | | | |
| Ross Flex, 250,000 Cycles | | | | | | | |
| Unaged Crack Growth, % | <100 | + | + | - | - | + | + |
| Aged 20 hours @ 250°F | | | | | | | |
| Crack Growth, % | <300 | + | + | + | - | + | + |
| DeMattia Flex | | | | | | | |
| Unaged Growth Rate, mils/min | <25 | + | + | + | + | + | + |
| Aged 20 hours @ 250°F | | | | | | | |
| Growth Rate, mils/min | <200 | + | + | + | + | + | + |
| Goodrich Flex @ 50°C | | | | | | | |
| Temperature Rise | | | | | | | |
| External, °C | <25 | + | + | - | + | + | + |
| Internal, °C | <50 | + | - | - | + | + | + |
| Heat Resistance | | | | | | | |
| at 160°F | | | | | | | |
| Compression Set, % (22 hrs) | <25 | - | - | - | - | - | + |
| at 212°F | | | | | | | |
| Compression Set, % (46 hrs) | <40 | + | - | - | - | - | + |
| at 250°F | | | | | | | |
| Elongation Retention, % | >70 | + | + | + | + | + | + |
| Tensile Retention, % | >70 | - | - | - | - | - | - |
| Compression Set, % (22 hrs) | <50 | - | - | + | - | + | + |
| at 300°F | | | | | | | |
| Elongation Retention, % | >60 | - | - | - | - | - | - |
| Tensile Retention, % | >60 | - | - | - | - | - | - |
| Compression Set, % (22 hrs) | <60 | - | - | - | - | - | + |

Table 7. Physical Properties—Propylene Oxide Compounds

| MATERIAL ID | | PO-19 | PO-19A | PO-22 |
|----------------------------------|----------------|--------------|---------------|--------------|
| Original Properties | Desired | | | |
| Tensile Strength, psi | >2700 | 1710 | 1713 | 1737 |
| 200% Modulus, psi | >700 | 757 | 1000 | 1567 |
| Elongation, % | >350 | 520 | 377 | 223 |
| Hardness, Shore A Points | 65 - 75 | 67 | 72 | 85 |
| Bashore Rebound, % | >50 | 49 | 50 | 49 |
| Compression Deflection, % | 33 - 41 | 41 | 39 | — |
| Specific Gravity | — | 1.2254 | 1.2236 | 1.2249 |
| Press Cure, min/°F | — | 50/300 | 50/300 | 40/290 |
| Oven Post Cure, hrs/°F | — | — | 16/250 | — |
| Tear Strength; ASTM Die C, lb/in | | | | |
| Unaged | >300 | 234 | 228 | 273 |
| 4 hours @ 250°F | >175 | 112 | 102 | 112 |
| 4 hours @ 300°F | >150 | 109 | 90 | 66 |
| Brittleness, 7 days @ -40°F | Pass | Pass | Pass | Pass |
| Fatigue Properties | | | | |
| Ross Flex, 250,000 Cycles | | | | |
| Unaged Crack Growth, % | <100 | 230 | 567 | Fail |
| Aged 20 hours @ 250°F | | | | |
| Crack Growth, % | <300 | Fail | Fail | Fail |
| DeMattia Flex | | | | |
| Unaged Growth Rate, mils/min | <25 | 64 | 180 | 356 |
| Aged 20 hours @ 250°F | | | | |
| Growth Rate, mils/min | <200 | 622 | 622 | 622 |
| Goodrich Flex @ 50°C | | | | |
| Temperature Rise | | | | |
| External, °C | <25 | 22 | 21 | 30 |
| Internal, °C | <50 | 46 | 46 | 73 |
| Heat Resistance | | | | |
| at 160°F | | | | |
| Compression Set, % (22 hrs) | <25 | 18 | 9 | — |
| at 212°F | | | | |
| Compression Set, % (46 hrs) | <40 | 54 | 31.5 | 81 |
| at 250°F | | | | |
| Elongation Retention, % | >70 | 61 | 98 | 87 |
| Tensile Retention, % | >70 | 95 | 100 | 87 |
| Compression Set, % (22 hrs) | <50 | 59.6 | 41.7 | 92 |
| at 300°F | | | | |
| Elongation Retention, % | >60 | 79 | 100 | 63 |
| Tensile Retention, % | >60 | 75 | 74 | 65 |
| Compression Set, % (22 hrs) | <60 | 66 | 53 | 99 |

Table 8. Conformance (Pass/Fail)—Propylene Oxide Compounds

| MATERIAL ID | | PO-19 | PO-19A | PO-22 |
|----------------------------------|----------------|--------------|---------------|--------------|
| Original Properties | Desired | | | |
| Tensile Strength, psi | >2700 | - | - | - |
| 200% Modulus, psi | >700 | + | + | + |
| Elongation, % | >350 | + | + | - |
| Hardness, Shore A Points | 65 - 75 | + | + | - |
| Bashore Rebound, % | >50 | - | + | - |
| Compression Deflection, % | 33 - 41 | + | + | ? |
| Tear Strength; ASTM Die C, lb/in | | | | |
| Unaged | >300 | - | - | - |
| 4 hours @ 250°F | >175 | - | - | - |
| 4 hours @ 300°F | >150 | - | - | - |
| Brittleness, 7 days @ -40°F | Pass | + | + | + |
| Fatigue Properties | | | | |
| Ross Flex, 250,000 Cycles | | | | |
| Unaged Crack Growth, % | <100 | - | - | - |
| Aged 20 hours @ 250°F | | | | |
| Crack Growth, % | <300 | - | - | - |
| DeMattia Flex | | | | |
| Unaged Growth Rate, mils/min | <25 | - | - | - |
| Aged 20 hours @ 250°F | | | | |
| Growth Rate, mils/min | <200 | - | - | - |
| Goodrich Flex @ 50°C | | | | |
| Temperature Rise | | | | |
| External, °C | <25 | + | + | - |
| Internal, °C | <50 | + | + | - |
| Heat Resistance | | | | |
| at 160°F | | | | |
| Compression Set, % (22 hrs) | <25 | + | + | ? |
| at 212°F | | | | |
| Compression Set, % (46 hrs) | <40 | - | + | - |
| at 250°F | | | | |
| Elongation Retention, % | >70 | - | + | + |
| Tensile Retention, % | >70 | + | + | + |
| Compression Set, % (22 hrs) | <50 | - | + | - |
| at 300°F | | | | |
| Elongation Retention, % | >60 | + | + | + |
| Tensile Retention, % | >60 | + | + | + |
| Compression Set, % (22 hrs) | <60 | - | + | - |

Table 9. Physical Properties—Silicone Compounds

| MATERIAL ID | | SI-5 | SI-6 | SI-7 | SI-8 |
|----------------------------------|----------------|-------------|-------------|-------------|-------------|
| Original Properties | Desired | | | | |
| Tensile Strength, psi | >2700 | 1192 | 1273 | 978 | 1225 |
| 200% Modulus, psi | >700 | 490 | 278 | 470 | 365 |
| Elongation, % | >350 | 530 | 760 | 690 | 820 |
| Hardness, Shore A Points | 65 - 75 | 66 | 65 | 76 | 65 |
| Bashore Rebound, % | >50 | 53 | 44 | 43 | 47 |
| Compression Deflection, % | 33 - 41 | 42 | 42 | 33 | 43 |
| Specific Gravity | — | 1.1569 | 1.1818 | 1.2245 | 1.1868 |
| Press Cure, min/°F | — | 10/340 | 10/340 | 10/340 | 10/340 |
| Oven Post Cure, hrs/°F | — | 4/392 | 4/392 | 4/392 | 4/392 |
| Tear Strength; ASTM Die C, lb/in | | | | | |
| Unaged | >300 | 172 | 231 | 242 | 249 |
| 4 hours @ 250°F | >175 | 111 | 163 | 204 | 185 |
| 4 hours @ 300°F | >150 | 107 | 139 | 171 | 134 |
| Brittleness, 7 days @ -40°F | Pass | Pass | Pass | Pass | Pass |
| Fatigue Properties | | | | | |
| Ross Flex, 250,000 Cycles | | | | | |
| Unaged Crack Growth, % | <100 | 92 | 208 | 533 | 150 |
| Aged 20 hours @ 250°F | | | | | |
| Crack Growth, % | <300 | Fail | Fail | Fail | 650 |
| DeMattia Flex | | | | | |
| Unaged Growth Rate, mils/min | <25 | 18 | 14 | 25 | 14 |
| Aged 20 hours @ 250°F | | | | | |
| Growth Rate, mils/min | <200 | 25 | 21 | 41 | 32 |
| Goodrich Flex @ 50°C | | | | | |
| Temperature Rise | | | | | |
| External, °C | <25 | 22 | 36 | 35 | 27 |
| Internal, °C | <50 | 47 | 80 | 84 | 51 |
| Heat Resistance | | | | | |
| at 160°F | | | | | |
| Compression Set, % (22 hrs) | <25 | 5 | 13 | 9 | 6 |
| at 212°F | | | | | |
| Compression Set, % (46 hrs) | <40 | 13 | 25 | 23 | 11 |
| at 250°F | | | | | |
| Elongation Retention, % | >70 | — | — | — | — |
| Tensile Retention, % | >70 | — | — | — | — |
| Compression Set, % (22 hrs) | <50 | 11 | 22 | 16 | 9 |
| at 300°F | | | | | |
| Elongation Retention, % | >60 | 87 | 94 | 96 | 89 |
| Tensile Retention, % | >60 | 95 | 95 | 92 | 87 |
| Compression Set, % (22 hrs) | <60 | — | — | — | — |

Table 10. Conformance (Pass/Fail)—Silicone Compounds

| MATERIAL ID | | SI-5 | SI-6 | SI-7 | SI-8 |
|----------------------------------|----------------|-------------|-------------|-------------|-------------|
| Original Properties | Desired | | | | |
| Tensile Strength, psi | >2700 | — | — | — | — |
| 200% Modulus, psi | >700 | — | — | — | — |
| Elongation, % | >350 | + | + | + | + |
| Hardness, Shore A Points | 65 – 75 | + | + | + | + |
| Bashore Rebound, % | >50 | + | — | — | — |
| Compression Deflection, % | 33 – 41 | — | — | + | — |
| Tear Strength; ASTM Die C, lb/in | | | | | |
| Unaged | >300 | — | — | — | — |
| 4 hours @ 250°F | >175 | — | — | + | + |
| 4 hours @ 300°F | >150 | — | — | + | — |
| Brittleness, 7 days @ –40°F | Pass | + | + | + | + |
| Fatigue Properties | | | | | |
| Ross Flex, 250,000 Cycles | | | | | |
| Unaged Crack Growth, % | <100 | + | — | — | — |
| Aged 20 hours @ 250°F | | | | | |
| Crack Growth, % | <300 | — | — | — | — |
| DeMattia Flex | | | | | |
| Unaged Growth Rate, mils/min | <25 | + | + | + | + |
| Aged 20 hours @ 250°F | | | | | |
| Growth Rate, mils/min | <200 | + | + | + | + |
| Goodrich Flex @ 50°C | | | | | |
| Temperature Rise | | | | | |
| External, °C | <25 | + | — | — | — |
| Internal, °C | <50 | + | — | — | — |
| Heat Resistance | | | | | |
| at 160°F | | | | | |
| Compression Set, % (22 hrs) | <25 | + | + | + | + |
| at 212°F | | | | | |
| Compression Set, % (46 hrs) | <40 | + | + | + | + |
| at 250°F | | | | | |
| Elongation Retention, % | >70 | — | — | — | — |
| Tensile Retention, % | >70 | — | — | — | — |
| Compression Set, % (22 hrs) | <50 | + | + | + | + |
| at 300°F | | | | | |
| Elongation Retention, % | >60 | + | + | + | + |
| Tensile Retention, % | >60 | + | + | + | + |
| Compression Set, % (22 hrs) | <60 | — | — | — | — |

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